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MAS-GRAS Sensor Combination and Optimal Estimation Retrieval of Temperature and H_2O Profiles

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Abstract. The results of a realistic simulation study in investigating the joint retrieval using measured temperature and water vapour data from the Space Shuttle based Millimeter wave Atmospheric Sounder (MAS) and from a GRAS (GPS/GLONASS receiver) sensor are presented. It seems highly worthwhile – because of the very impressive results – to place a MAS Follow-on sensor together with a GRAS sensor on the EXPRESS Pallet of the International Space Station (ISS). It is a role model of synergetic use of sensors in the best sense. An international feasibility study shows that this is technically feasible.

1 The MAS Follow-on concept and the addition of GRAS

The Millimeter-wave Atmospheric Sounder (MAS) has been successfully flown as a core payload of the three NASA ATLAS Space shuttle missions. It has recorded microwave emission spectra of the Earth's atmosphere allowing to retrieve temperature, pressure, ozone, water vapour, and the anthropogenic produced chlorine monoxide which mainly causes the depletion of the stratospheric ozone layer (Hartmann et al., 1996). In the next chapter we show the results of a realistic simulation study in investigating joint retrieval based on both MAS data and GRAS (GPS/GLONASS Receiver for Atmospheric Sounding) radio occultation data. It showed that this allows to achieve very favourable accuracy of temperature profiles of the Earth's atmosphere, i.e. this method – combined with a so called assimilation of model based data – presents hitherto the most efficient data validation*. Thus a combination of a MAS Follow-on experiment – i.e., a modified MAS with second generation radiometers, electronics, and a star sensor – together with a GRAS receiver on the EXPRESS Pallet of the International Space Station (ISS) is highly recommended. This would allow to obtain not only more accurate temperature and water vapour profiles but also provide simultaneously liquid water data below 17 km. All these quantities are very important for climatological research. A possible configuration of this combination is shown in figure 1.

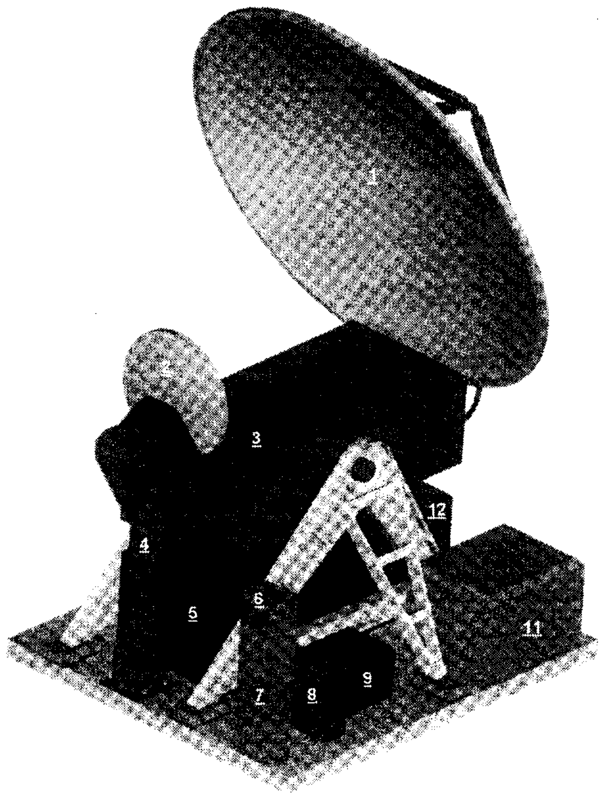

Fig. 1. MAS Follow-on with GRAS sensor on the EXPRESS Pallet of the International Space Station (ISS)
1. Main-Reflector, 2. Sub-Reflector, 3. MRE (MAS Receiver Electronics) and IR (Infrared Sensor), 4. LA Linear Actuator, 5. FEB (Filter Electronic Box), 6. Star-Tracker with electronic box inside, 7. Place for GPS sensor, 8. Electronic Box for GPS system, 9. MCE (Motor Control Electronics), 10. Adapter to ISS EXPRESS Pallet, 11. PEB (Power Electronic Box), 12. DIB (Digital Electronic Box) with ROB (Reference Oscillator Box). See also http://www.linmpi.mpg.de/english/projekte/mas/html/mas_expa_iss.htm. There can be found also more detailed information about MAS.

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* Remark: **Data validation**: systematic errors can only be measured if the same physical object is measured at least once more with a measuring configuration based on a different principle from the first. The comparison of these two (or more) sets of data is called validation. The degree of agreement between the two sets of data (a standard established **intersubjectively** by the scientific community) determines the "value" of the data, i.e. the degree of reliability the data can claim, i.e. their quality. Data validation is unthinkable without this **participation by the community.** (The value thus determined is called **"accuracy"** (indeterminacy)). **Data verification** means repeating the measurement independently with the same equipment, using the same hypotheses and references, and then comparing the results. The cross-correlation between two sets of data ob- tained independently of one another is a gage for the verification, whose standard (quantitative value) has to be agreed on **intersubjectively** by the scientific community. (The value thus determined is called **"precision"** (indeterminacy)).

Table 1. Measured quantities by combining MAS Follow-on (M) with GRAS (G):

Quantity	MAS frequency	Height Range [km]
Temperature	61 GHz	0-50 (G) + 15-90 (M) = 0 - 90
Pressure	62 GHz	0-50 (G) + 15-90 (M) = 0 - 90
H_2O	180 GHz	< 7 km (G) + > 7 km (M)
H_2O	183 GHz	17 - 95 (M)
O_3	184 GHz	17 - 95 (M)
ClO	204 GHz	17 - 45 (M)

2 MAS-GRAS combined temperature retrievals

We investigated, with the aid of the optimal estimation method (Rodgers, 2000), the retrieval accuracy of temperature profiles from MAS-only and GRAS-only data analysis and, of par- ticular interest, from combined MAS-GRAS data analysis. Here we focus on a brief presentation of the combined analysis; for information on single-sensor performance analyses see Von Engeln *et al.* (1998) for MAS and Kirchengast and Ramsauer (1998) for GRAS, respectively. The optimal estimation jointly using MAS and GRAS data allows the retrieval of a single hybrid temperature profile, spanning the full altitude range from surface to mesopause (0 km to 90 km).

MAS and GRAS sensor data were simulated based on a realistic sounding geometry assuming the sensors mounted on an ISS EXPRESS Pallet and probing the same air volumes toward the backward limb. A representative sample of 30 globally distributed GRAS occultation events and co-located MAS limb sounding scans were "forward–modelled" using temperature fields based on the MSIS-90 model (Hedin, 1991). The End-to-end GNSS (Global Navigation Satellite System; generic term for GPS and GLONASS) Occultation Performance Simulator, (EGOPS) software tool was employed for these simulations (for details on EGOPS and the simulations see Kirchengast, 1998; Kirchengast and Ramsauer, 1998). Figure 2 shows a typical latitude-height cross section through the global MSIS-90 temperature field utilized.

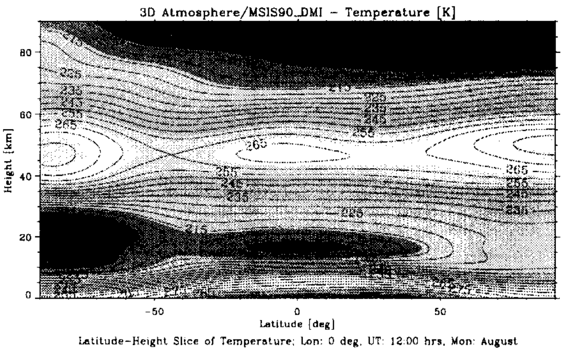

Fig. 2. Example cross section through MS/S-90 model

Temperature retrievals were then performed by optimal estimation on a case-by-case basis and retrieval error statistics were produced based on the ensemble of retrieved profiles. We found a modern MAS-GRAS sensor to achieve < 1 K accuracy below 35 km at 1 km resolution and < 4 K accuracy throughout the mesosphere at 5 km resolution. This is illustrated in Figure 3, where results for 3 different MAS system temperatures are shown of which the $T_{Sys} = 500$ K case is the one the MAS Follow-on instrument is expected to meet.

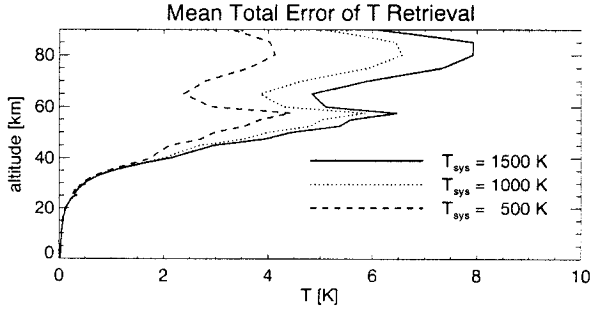

Fig. 3. Statistical error for MAS/GRAS sensor

An individual exemplary case of a retrieved temperature profile is depicted in Figure 4. The left panel highlights both assumed *a priori* uncertainties and retrieval errors, respectively, while the right panel shows the combined MAS-GRAS "averaging kernels" (see Rodgers, 2000, on the meaning and role of averaging kernels). The latter panel instructively indicates the high synergy in information contribution by the two sensors: GRAS contributions, characterized by high vertical resolution (narrow averaging kernels), dominate up into the upper stratosphere, within which a smooth transition to a dominance of MAS contributions (broader averaging kernels) above the stratopause occurs.

A detailed description of the MAS-only, GRAS-only, and

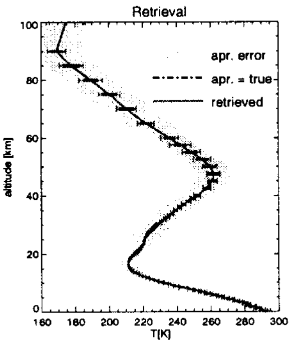

Fig. 4. T retrieval example – profiles and Av. kernels

combined MAS-GRAS optimal estimation retrieval work was provided by Von Engeln *et al.* (1999). Kirchengast and Ramsauer (1998) performed an important predecessor study, which mainly dealt with GRAS-only temperature retrieval performance but strongly indicated already the potential of joint MAS-GRAS retrievals for both temperature and water vapour profiling throughout the lower and middle atmosphere.

3 GRAS H_2O retrieval results

The retrieval accuracy of water vapour (H_2O) profiles from GRAS data was studied as well. For this parameter, the retrieval altitude range was restricted to the first scale height above surface (< 8 km), where the GRAS data contain sufficient information for this purpose. For temperature, which was simultaneously retrieved from the combined MAS and GRAS data, the same setup as described in section 2 above was used, with a retrieval grid again ranging over the full lower and middle atmosphere.

Extracting 3 occultation event locations and the corresponding geometrical data from the ensemble of 30 used in section 2 above, three representative moist-air cases were simulated with the EGOPS tool, respectively, a dry, a medium moist, and a moist case. The enhanced CIRA-86 moist atmosphere climatology model CIRA86aQ_UoG (Kirchengast *et al.*, 1999) was invoked for furnishing the temperature and humidity fields for the "forward modelling" of these moist-air occultation data.

It was found that water vapour can be retrieved (by optimal estimation) from GRAS data to within 10 % accuracy below ~ 3 to 6 km and to better than 20 % below ~ 6 to 8 km, respectively. This is illustrated by Figure 5, which depicts moist air retrieval results for the 3 selected cases when an *a priori* water vapour uncertainty of 25 % and an *a priori* temperature uncertainty of 2 K was adopted. These *a priori* assumptions are quite reasonable in that they reflect typical uncertainties in short–range (6 to 12 hrs) forecast fields of numerical weather prediction models, which are the usual source of *a priori* profiles if satellite data are exploited in operational meteorology. Temperature retrievals in moist air are found to be accurate at the 1 K level (Fig. 5, left panel). Note that the results for water vapour (Fig. 5, right panel) are depicted in terms of a "retrieval-to-*a priori* error ratio", which expresses the fraction of the *a priori* error to which the retrieval error corresponds (e.g., 0.4 corresponds to 10 % retrieval accuracy given 25 % *a priori* uncertainty). Von Engeln *et al.* (1999) describes the H_2O–related retrieval scenarios and the corresponding results obtained in detail.

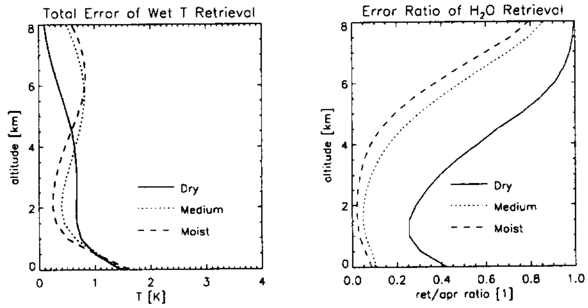

Fig. 5. Moist air retrieval – 3 scenarios

4 The need for joint MAS-GRAS H_2O retrievals

Water is the only substance that occurs not only in all three phases, gaseous, fluid, and solid in the Earth's atmosphere but also in transitions between them like in its "polymer forms"-clusters, clathrates, aerosols. Although the importance of the solid and fluid forms is popularly understood, there is less general understanding of the role of water vapour and especially for its polymer forms than, for example, of carbon dioxide (CO_2) or ozone (O_3).

The spatial and temporal distributions of the various phases of water in the atmosphere are in fact very important factors to climate, weather, the biosphere, the homogeneous and inhomogeneous chemistry of the atmosphere, as well as to the propagation of electromagnetic waves used in transatmospheric (global) navigation and communication systems and for relevant remote sensing measurements. In this context the atmosphere acts like a temporal and spatial variable, frequency dependent filter.

Despite the fact that above the tropopause, i.e. in the stratosphere and mesosphere, there is less than 0.1 % of the total water vapour content of the Earth's atmosphere its influence is very significant for the physics and chemistry of the upper atmosphere and hence for the climate. Some questions concerning the H_2O occurrence and its variations in the Earths atmosphere, have been addressed by Hartmann (2000).

It has been recently shown that the accuracy of radiosonde (H_2O) humidity measurements, e.g. with Vaisala Humicap humidity sensors, strongly suffers from aging – outgassing – effects (Westwater et al., 1999a). The suppliers of these sondes now try to remove this effect at a reasonable costs. This however, implies, that until now these humidity data can only insufficiently or not be used for (longer term) climatological trend research, i.e. for the "calibration" of relevant H_2O remote sensing measurements. Because of these problems the opposite right now occurs, namely the calibration of radiosondes humidity measurements with microwave remote sensing data (Gueldner and Spankuch, 1999; Niell et al., 1999; Solheim et al., 1999; Westwater, 1999b). It was also recently shown by A. Gasiewski (NOAA ETL, Boulder, CO., USA) in a private communication that the calibration of the present DMSP H_2O radiances is hitherto insufficient for the investigations of small trends, i.e. for climatological research or relevant "calibrations". At MPAE this terminated the attempts of a value added validation of the MAS H_2O data. This was also much influenced by the fact that there has been insufficient co-location and co-time for such validation (verification) work with relevant UARS MLS H_2O data, mainly because of the large temporal and spatial variablitiy of the water vapour distribution in the Earth atmosphere.

These new findings direct now the attention to the use of GNSS H_2O data (Ware et al., 2000), which predominantly yield columnar (integrated) water content, i.e. precipitable water. Furthermore it fosters co-located and co-timed multi spectral measurementes of the atmosphere in the millimeter and submillimeter range together with "hyperspectral" optical imagers (Klein and Gasiewski, 2000) from the ground, aircrafts, balloons, and from space. Very interesting in this context is the "Peacewing" proposal of A. Gasiewski, for which he asks for further participants. All these multispectral measurements will allow in most cases joint retrieval calculations for various H_2O data. They will provide especially H_2O height profiles in a similar manner as shown in section 2 ?? for the MAS-GRAS temperature profiles.

While the MAS measurements are based upon the information that is contained in the imaginary part of the refractive index of the Earths atmosphere, GRAS uses complementary to it its real part. Therefore the information gain for the joint MAS-GRAS temperature retrieval is (optimally) high. If an height overlapp can be obtained also for the H_2O MAS-GRAS measurements – theoretically by using also 20 GHz measuring channels for MAS – then the same can be expected for a joint H_2O retrieval. It should be noted that the MAS Follwow-on measurements would also provide simultaneoulsy liquid water profiles below 17 km. All these quantities are very important for climatological research.

5 Conclusions

It seems highly worthwhile to place a MAS Follow-on sensor together with a GRAS sensor on an EXPRESS Pallet of the International Space Station (ISS). In fact it were a role model of synergistic use of sensors in the best sense.

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